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**Structure from Motion used to revive archived aerial photographs
for geomorphological analysis: an example from Mount Meager
volcano, British Columbia, Canada**

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Abstract

High resolution topographic modeling has become more accessible due to the development of Structure from Motion (SfM) image matching algorithms in digital photogrammetry. Large archival databases of historical aerial photographs are available in university, public, and government libraries, commonly as paper copies. The photos can be in poor condition (i.e. deformed by humidity, scratched, or annotated). In addition, the negatives, as well as metadata, may be missing. Processing such photos using classic stereo-photogrammetry is difficult and, in many instances, impossible. SfM can be applied to these photosets to access the valuable archive of geomorphic changes over the past century. In this paper, we illustrate the utility of the SfM technique using 568 digitized vertical aerial photographs of Mount Meager volcano, located in southwest British Columbia, Canada. We use the aerial photographs, which span the period from 1947 to 2006, to track glacier and glacier-landslide interactions on the volcano. Over this period, glaciers have thinned and retreated, interrupted by minor advances in the 1960s and 1970s. Landslides are frequent on the volcano and contribute to debris cover on the glaciers affecting the ablation process. SfM processing of the aerial photographs allowed us to unlock geomorphic information and reconstruct landscape change that would otherwise have been impossible. The results from SfM provide a visually effective way of presenting landscape change to a broad public audience, as a form of virtual geoheritage. The approach can thus be broadly applied in scientific and professional practices for improving land planning and hazard management.

Keywords: historical aerial photographs, Structure from Motion, glacier change, landslides, debris-covered glaciers

Introduction

Reconstructions of geomorphic change over time are fundamental in many landform and natural hazard studies. Such landscape reconstructions are essential for following the

41 evolution of features that might cause landslides, and can inform about landscape changes
42 that can be integrated into landscape planning. Natural hazard and land planning studies
43 take into account that landforms are not static features, in support of these studies, aerial
44 stereo-photogrammetry is commonly used to produce topographic models and large-scale
45 topographic maps through time, leading to the collection of a large number of vertical aerial
46 photographs. The photographs commonly record Earth surface features that have changed
47 over time or have completely disappeared, and they cover remote and difficult-to-access
48 areas (e.g. high mountains and glaciated terrain) where establishing ground control is
49 difficult or impossible (Chandler, 1999; Lane et al., 2000; Gomez, 2014, 2015; Micheletti et
50 al., 2015). Although historic aerial photographs are a unique and valuable resource for
51 documenting surface changes over the 20th century (Bjørk et al., 2012; Tennant and
52 Menounos, 2013; Gomez et al., 2015), they are not extensively used for this purpose and
53 commonly lie forgotten in university, government, public, and private libraries. Paper copies
54 of old aerial photographs are commonly deformed by moisture, scratches, or annotations,
55 and the original negatives or metadata on cameras and flight missions may be missing. In
56 these cases, it is difficult to retrieve topographic information from aerial photographs using
57 classical digital photogrammetric techniques, although there are exceptions (e.g. Krimmel,
58 1999; Lucchesi et al., 2013; Tennant and Menounos, 2013).

59 The Structure from Motion (SfM) method can provide quantitative topographic and
60 geomorphic information from historic aerial photographs also when these are not in perfect
61 conditions and metadata may be missing (Gomez, 2014; Gomez et al., 2015; Bakker and
62 Lane, 2016; Mertes et al., 2017; Mölg and Bolch, 2017; Roberti et al., 2018b). In this paper
63 we use SfM and airphotos collected over a nearly 60-year period (1947-2006) and Lidar data
64 collected between 2015 and 2016 to document glacier change and landslide activity over in
65 five watersheds draining Mount Meager, a glacier-clad volcanic complex in southwest British
66 Columbia, Canada (Figure 1). Our objective is to show the value of using SfM on historical
67 aerial photographs to document recent geomorphic change by providing an effective

workflow that can be used in slope hazards and glacier dynamic change investigations. The time dimension and graphical three-dimensional display significantly increases the power to communicate this change and to increase awareness of the importance of geomorphologic changes to a wider audience.

SfM principles and applications

The origin of SfM dates back to the 1970s with the formulation of the Structure from Motion theorem. SfM is the computer vision algorithm used to generate three-dimensional point clouds (structure) in generic object coordinates from photographs taken by a moving sensor (motion) (Ullman 1979). In the geosciences, the term SfM refers to a composite workflow SfM-multi-view stereo (MVS) algorithm (James and Robson 2012, Westoby et al. 2012, Carrivick et al. 2016). The SfM-MVS algorithm first generates a sparse point cloud and then creates a dense point cloud by increasing the number of points by the MVS method. Modern SfM was developed in the 1990s as digital imagery increasingly became available. It began to be used by the geosciences community in the past decade: Cecchi et al. (2002, 2003) applied it to laboratory models and aerial images acquired by a hand-held camera and Snively et al.(2008) reconstructed cities from photos randomly acquired by tourists. Today, SfM is used in all fields of Earth science, from hand-sample-scale reconstructions to medium-scale topographic modeling (James and Robson 2012). The technique is commonly employed with photographs taken at ground level or from the air with unmanned aerial vehicles (UAV) with digital or analog cameras (Carrivick et al. 2016, James et al. 2020). However, to date, few studies have explored the possibility of processing archival aerial photographs taken during the past century for diachronic geomorphic studies (Gomez 2014, Derrien et al. 2015, Gomez et al. 2015, Rault et al. 2020)

The great step forward of SfM from traditional digital photogrammetry is the use of amateur non-metric cameras instead of professional metric cameras, and the automatic internal photo error calculations that allow the processing of hundreds of frames at once. SfM

94 algorithms have been developed to work with off-nadir convergent photos (Snavely et al.,
95 2008; Furukawa and Ponce, 2010). They provide three-dimensional reconstructions of
96 objects and surfaces from sets of overlapping images, without the need for pre-calibrated
97 metric cameras, ground control, or any other external information (Cecchi et al., 2002,
98 2003). The collinearity equations, which are the function describing the relation between
99 coordinates in two dimensional photographs and the three-dimensional real object
100 coordinates, are solved from redundancy of images (Szeliski 2010), hence three-
101 dimensional model is built a priori, in generic x, y, z object coordinates. SfM photo matching
102 is based on multiple-scale, image-matching algorithms (e.g. the scale invariant feature
103 transform, SIFT; Lowe, 1999), where every pixel is matched (Hirschmüller et al. 2012).
104 These algorithms recognize pixel gradients (e.g. shapes) to identify large numbers of
105 common features between images. The ability to recognize shapes enables matching of
106 photos with different scales, translations, rotations, and brightness levels; it also allows
107 objects to be separated from the background (Fonstad et al. 2013). The camera parameters
108 are derived from self-calibration during the bundle adjustment (where all images are bundled
109 together in one 3D processing batch). The quality of SfM-derived, 3D point data depends
110 only on the scale and quality of the pictures. The use of accurate ground control point,
111 although not required, can improve the bundle adjustment (Carrivick et al. 2016, James et al.
112 2017b) and provides georeferenced models, orthophotos, and digital surface models
113 (DSMs). When ground control is unavailable, these products can still be generated and scaled
114 to real world dimensions, albeit with less accuracy, by defining distances between
115 recognizable points.

116 **Methods**

117 We digitized 568 vertical aerial photographs and used the commercial SfM software
118 PhotoScan to produce orthophotos and DSMs. PhotoScan delivered high-resolution
119 orthophotos (0.42-1.13 m/pixel) and DSMs (1-5 m/pixel), suitable for our geomorphic study

(Table 1). We processed part of the same dataset as that of Roberti et al. (2018b) using vertical black-and-white aerial photographs of Mount Meager taken in 1947, 1951, 1962, 1964-1965, 1973, 1981, and 1990, and colour photos taken in 2006. We also used an aerial Lidar digital terrain model (DTM) constructed from data acquired in 2015 and 2016 to assess the SfM-derived orthophoto quality and extend the period of geomorphic analysis by an additional decade. Lidar data was acquired with a Riegl VQ-580 scanner equipped with an Applanix POS AV910 inertial measurement unit/GNSS receiver for geolocation and orientation of the scanner relative to the surveyed terrain. The Southern sector of the volcano was surveyed in 2015 whereas the Northern half of the volcano was surveyed in 2016. Point cloud density averaged 2.57 points m⁻², and we generated 1 m terrain models from these data

For this study, we processed images from 1947, 1962, 1964-1965, 1973, 1990, and 2006.. We included images taken 1947 and 1962 despite some deficiencies: the 1947 dataset covers the entire massif, but clouds partly obscure the land surface; the 1962 photos overlap poorly in the center of the massif, and snow covers most of the slopes.

Image digitization

We used an A3 format non-photogrammetric flatbed scanner to digitize the aerial photographs. The declared 2D deformation is anisotropic and about 200 microns. This deformation can be corrected by the SfM procedure. To avoid uncontrolled deformations each photo was scanned with the flight direction parallel to the charges-coupled device (CCD) array, based on the recommendation of Linder (2009). The minimum DPIs (dots per inch) required for the scans were derived from the scale factor (S) of the photographs (Supplementary material B). The photos and their metadata are listed in Table 1.

PhotoScan processing

We used Agisoft PhotoScan Professional v1.2.6 SfM software (www.agisoft.com; now Metashape, Agisoft LLC, St. Petersburg, Russia) to process the digitized aerial photographs.

We chose PhotoScan because it is widely used in the geosciences, has been proven to be reliable (Remondino et al., 2014; James et al., 2017), and includes a complete workflow from image matching to three-dimensional dense point cloud reconstruction, georeferencing, and orthophoto and DSM generation. We followed the standard PhotoScan workflow to generate orthophotos and DSMs, with particular attention to masking, referencing steps, and optimization steps. We masked photo frames and inscriptions to speed-up the processing and to prevent artifacts from appearing in 3D models, orthophotos, and DSMs. We defined 22 ground control points (GCPs) on available satellite images and DEMs to reference 3D models. Planimetric coordinates were derived from satellite SPOT 10 m imagery, and vertical coordinates from the Canada TRIM (Terrain Resource Inventory Map) DEM (18.3 m average accuracy) (Natural Resources Canada 2013). We used the Lidar DTM only for cartographic validation and not for georeferencing because we wanted to use a workflow that does not require Lidar and in which measurements can be done in relative coordinate systems. We selected ground control points in meadows, on glacier-polished bedrock, on Little Ice Age moraines, along logging roads, and on other recognizable features. Not all the points are visible in all the datasets. In old aerial photographs, for example, logging roads are not present and many higher elevation points are covered by snow.

Artifacts (e.g. steps, bumps etc..) or voids are commonly generated in areas lacking texture, for example on glaciers and snowfields, in forested areas, and where shadows are present. Clouds can also obscure parts of the landscape, generating errors in the 3D models. Careful manual visual model examination was required to identify and delete artifacts. Table 1 summarizes the model characteristics as provided by PhotoScan for the different photo datasets, and further details on the processing are included in Supplementary material A.

Cartographic validation

The cartographic quality of the PhotoScan-generated orthophotos and DSMs was tested by comparison with the 2015-2016 Lidar DTM. We followed two different approaches to assess

the SfM products (Figure 2). First, we compared x, y, and z coordinates of 22 independent control points between the PhotoScan models and the Lidar reference. Secondly, we did raster-to-raster differencing between the PhotoScan models and the Lidar data to evaluate the DSM quality. Then, to reduce systematic errors (e.g. tilting, doming), we 1) re-aligned a subset of the photos and 2) co-registered DSM subsets in CloudCompare (Girardeau-Montaut 2018). Photo re-alignment and DSM co-registration improved the quality of the DSMs, allowing more precise DSM comparison and volume calculations. We will not discuss DSM co-registration as it has been already explored by (Roberti et al. 2018b) and focus instead on 2D processing over large areas.

We compared x, y, and z coordinates of 22 control points (CP) that are not the same as those used in the PhotoScan workflow between the PhotoScan models and the Lidar DTM. Following American Society for Photogrammetry and Remote Sensing guidelines (ASPRS 2014), we used the root mean square error (RMSE) of x, y, z coordinates to evaluate the accuracy of the SfM-derived cartographic products. We calculated the RMSE of at least 20 of the 22 CPs (not all points are visible in all photos) taken from the PhotoScan exports and the reference Lidar DTM. The values are $RMSE_x$, $RMSE_y$, $RMSE_z$, and $RMSE_r$, the last being the horizontal linear RMSE, which includes both x- and y- coordinate errors. The horizontal accuracy at the 95% confidence level (HA 95%) and the vertical accuracy at the 95% confidence level (VA 95%) (ASPRS 2014) are approximately the same as the maximum error on either side of the mean of 95% of the planimetric and altimetric values. Table 2 summarizes $RMSE_x$, $RMSE_y$, $RMSE_z$, $RMSE_r$, HA 95, and VA 95 for the Lidar and photo check points. Horizontal georeferencing errors for these points range from 19 to 86 m; the corresponding vertical errors range from 15 to 176 m.

During georeferencing a rigid seven-parameter transformation was applied to translate, scale, and rotate the model to fit the real world location. Ideally, GCPs should be located in flat stable areas, far from cliffs, that are easy to recognize and access. At Mount Meager, it is very challenging to find points with these characteristics. Snow and glaciers cover the

volcano, the valley flanks have very active channels or are forested, and access to the area is challenging and dangerous. The rigid transformation applied during georeferencing cannot correct non-linear errors that may be present in the model. Non-linear errors can be related to poor picture overlap, object texture or shape, or lens and scanner deformation. In order to partially correct these types of error, PhotoScan recommends that the user optimizes the estimated point cloud, camera position, and camera parameters based on GCPs. However, if the GCPs have low accuracy, they can introduce additional errors. In our case, the GPS planimetric accuracy is >10 m and the vertical accuracy is >40 m, thus the PhotoScan alignment precision is greater than the GCP accuracy and so we generally did not proceed to optimize the point clouds.

GIS mapping

We describe the geomorphological evolution of the five main catchments on the Mount Meager massif (Figures 3-7). The following geomorphic features are used to describe the catchments: glacier length, which is defined as the map distance from the highest point on the glacier to its terminus; and the glacier watershed, which includes the steep slopes surrounding the glacier. The watershed headwalls are also described as they contribute avalanche snow and rockfall to the glacier surface. We also delineated stagnant ice near the terminus of the glacier based on the presence of hummocky topography and lack of crevasses. All features, including glacier outlines, moraines, landslide deposits, scars, and fractures, were mapped at 1:20,000 scale.

In light of the high georeferencing errors, we did not directly compare the coordinates of the moraines and glacier fronts in the different datasets; rather we worked in relative coordinate systems. We defined reference lines between recognizable and relatively stable landscape features (moraines, tension cracks) and measured the distance (in meters) between the lines and the geomorphic features. Then we compared these distances in the different photo datasets. For Devastation Glacier, the reference line extends through the apex of the large

1947 landslide scar (Figure 3 H). For Mosaic Glacier (Figure 4 I), Job Glacier (Figure 5 J), and Plinth Glacier (Figure 7 I), the reference lines pass through gullies in their respective Little Ice Age moraines. In the case of Affliction Glacier, we established a line that intersects a tension crack near the glacier's Little Ice Age limit (Figure 6 J). Distances from reference lines are not affected by georeferencing errors, because the models were not "optimized" using ground control point coordinates to correct the bundle adjustment errors. GCPs were used only to scale and rotate the models to approximate real world coordinate (see supplementary material A for processing details). Reference lines are affected by bundle adjustment errors and polygon digitization errors, which depend on the mapping scale, operator precision, and the model precision (pixel error). This procedure provides relatively precise measurements even on poorly georeferenced maps, as long as the SfM bundle adjustment is sufficiently precise. In our study, the PhotoScan bundle adjustment error (pixel error) of all datasets (0.6-2.2 m) is less than the graphical error (Gomasca 2009) at a scale of 1:20,000 (4 m), giving us confidence in the accuracy of the relative coordinate measurement approach. We calculated average glacier retreat rates by dividing distances between the glacier front and the reference line by the number of years between the datasets being compared.

Results: Geomorphic changes at Mount Meager volcano

Devastation Glacier

In 2016, Devastation Glacier was 3.7 km long and extended through an elevation range of 1400-2200 m asl. The glacier flows southeast from an ice cap that also feeds Mosaic and Affliction glaciers. The catchment area is 3 km² and has steep headwalls up to 0.7 km high (Table 3).

Large landslides are visible in 1947 and 1975 photos deposited debris on the glacier, which was subsequently deformed into arched debris ridges that mimic frontal moraines. The 1947

250 aerial photographs show fresh landslide debris on the ablating glacier surface (Figure 3 A).
251 The landslide scar has a triangular shape that is 0.26 km high and 0.27 km wide at the base.
252 The landslide traveled 1.8 km, 1.7 km of which was on the glacier surface. The vertical drop
253 was 0.5 km; thus the landslide had a *fahrböschung* (travel angle) of 15°. The landslide was
254 constrained by lateral moraines and it split into two lobes after overtopping a debris ridge on
255 the glacier. Active ice extends 1.2 km beyond the limit of the 1947 landslide deposit. The
256 lowermost 0.5 km of the glacier appears to be stagnant which is evidenced by hummocky
257 topography. The glacier in 1947 was larger than at any other time in the 60-year photo
258 period (1947-2006). By 1962 the glacier had deformed the 1947 landslide debris into two
259 arched debris ridges. In the 1962 photos, an arched ridge marks the up-glacier end of the
260 debris sheet, and an S-shaped ridge is present at its lower limit (Figure 3 B). Both ridges
261 moved downstream at a rate of $\sim 11 \text{ m yr}^{-1}$ between 1962 and 1981. In the 1981 photos, the
262 two ridges are covered by debris of the large landslide that occurred in 1975, but are still
263 recognizable. Down-glacier movement of the ridges increased to $\sim 28 \text{ m yr}^{-1}$ between 1981
264 and 1990, but then decreased to $\sim 6 \text{ m yr}^{-1}$ between 1990 and 2016. In the 2006 images, the
265 lower ridge is unrecognizable and the upper ridge is eroded.

266 The slope that failed in 1975 is partly obscured by clouds and snow in the 1947, 1962, and
267 1973 photos, although antithetic scarps are visible on the lower part of the slope (Figure 3 A,
268 B, and C). The 1981 photos clearly show the headscarp of the 1975 landslide, its travel path,
269 and the debris on the glacier. The headscarp is 0.3 km wide and 1 km high (Figure 3 D), and
270 the deposit extends 6.7 km to the confluence of Devastation and Meager creeks. The
271 vertical drop is about 1.2 km over that distance, yielding a *fahrböschung* of 10°. The
272 landslide volume estimate is $26 \times 10^6 \text{ m}^3$ (Mokievsky-Zubok, 1977). By 1981, the landslide
273 debris had been deformed into an arched debris ridge. This ridge advanced at an average
274 rate of $\sim 20 \text{ m yr}^{-1}$ between 1981 and 1990, $\sim 9 \text{ m yr}^{-1}$ between 1990 and 2006, and $\sim 5 \text{ m yr}^{-1}$
275 between 2006 and 2016. By 2006, the 1975 debris ridge had been breached (Figure 3 F).

The glacier terminus retreated 1.7 km between 1947 and 2016. The average rate of retreat of the stagnant ice terminus is $\sim 16 \text{ m yr}^{-1}$ between 1947 and 1973, $\sim 76 \text{ m yr}^{-1}$ between 1973 and 1981, $\sim 6 \text{ m yr}^{-1}$ between 1981 and 2006, and $\sim 51 \text{ m yr}^{-1}$ between 2006 and 2016 (Figure 3 I). The active ice terminus retreated at an average rate of $\sim 14 \text{ m yr}^{-1}$ between 1947 and 1973 and $\sim 88 \text{ m yr}^{-1}$ between 1973 and 1981. However, it advanced at an average rate of $\sim 13 \text{ m yr}^{-1}$ between 1981 and 1990, before retreating at $\sim 10 \text{ m yr}^{-1}$ between 1990 and 2016 (Figure 3 A-I).

Mosaic Glacier

In 2016 Mosaic Glacier extended 3 km from 2200 to 1600 m asl. The north-facing basin in which the glacier sits has an area of 2.5 km^2 . There are no significant cliffs that shed debris onto Mosaic Glacier, and the bedrock is constituted by Mesozoic intrusive igneous rocks (Read 1990) not part of the Mount Meager volcanic sequence (Figure 1).

Mosaic Glacier was obscured by clouds when the 1947 photos were taken. It retreated 1.9 km between 1951 and 2016 (Figure 4 A-H). The average rate of retreat is $\sim 49 \text{ m yr}^{-1}$ between 1951 and 1964, $\sim 20 \text{ m yr}^{-1}$ between 1964 and 2006, and $\sim 45 \text{ m yr}^{-1}$ between 2006 and 2016 (Figure 4 H). Sometime between 1962 and 1964, the western lateral moraine collapsed onto the glacier surface (Figure 4 C). By 2006, this deposit has been eroded by the proglacial stream (Figure 4 G).

Job Glacier

In 2016 Job Glacier was 2.8 km long, and descended from 2000 to 1200 m asl. The glacier is bordered at its head by a steep headwall, up to 0.5 km high. The large north-facing amphitheater (2.8 km^2) in which the glacier lies is partly the product of many Holocene landslides (Figure 1; Jordan 1994; Simpson et al., 2006; Friele et al., 2008).

The glacier in 1947 was larger than at any time in the photographic record, and its snout was covered by debris. In 1947, a streak of dark material is visible at the site where an ice cave

and fumarole were discovered in 2016 (Roberti et al., 2016; Figure 6 A). The front of the glacier retreated 0.7 km between 1947 and 2016 (Figure 5 A-K). The average rate of retreat is $\sim 28 \text{ m yr}^{-1}$ between 1947 and 1964, and $\sim 11 \text{ m yr}^{-1}$ between 1981 and 2016. The glacier advanced between 1964 and 1981 at an average rate of $\sim 12 \text{ m yr}^{-1}$.

In 1990 photos, a debris streak 1 km long and up to 0.2 km wide is visible on the west portion of the glacier, indicating a recent landslide. Through the photo record, the west and east valley flanks adjacent to the glacier show signs of instability (Roberti et al. 2018a): the east flank is highly deformed and dissected by numerous tension cracks and slip surfaces; recent large failure scars are also present. The west flank is a prominent bulge identified by a major failure slip plane, smaller scar and counter scarps are found in the lower part of the slope.

Affliction Glacier

In 2016 Affliction Glacier was 3.2 km long and descended from 2200 m to 1500 m asl. It is bordered by a 0.3-km-high cliff that sheds debris onto the west part of the glacier. The glacier basin faces north and has an area of 3.6 km^2 .

The glacier retreated 0.3 km from 1947 to 2016 (Figure 6 A-K). The average rate of glacier retreat is $\sim 15 \text{ m yr}^{-1}$ between 1947 and 1964, and $\sim 6 \text{ m yr}^{-1}$ between 1981 and 2016. The glacier advanced at an average rate of $\sim 11 \text{ m yr}^{-1}$ between 1964 and 1981. Both valley sides are marked by antithetic scarps and fractures (Bovis 1990).

Plinth Glacier

Plinth Glacier is located in a steep-sided, northeast-facing amphitheater (1.5 km^2) produced by an eruption of the volcano about 2400 years ago (Clague et al. 1995, Stasiuk et al. 1996). In 2016 the glacier was 1.1 km long and extended from 1700 to 1200 m asl. The glacier is bordered by an up to 1-km-high headwall (Table 3).

Clouds obscured Plinth Glacier in 1947 when the aerial photographs were acquired. Between 1951 and 1990, the glacier advanced at an average rate of $\sim 8 \text{ m yr}^{-1}$. It receded between 1990 and 2006 at an average rate of $\sim 15 \text{ m yr}^{-1}$, but advanced again between 2006 and 2016 at a rate of $\sim 4 \text{ m yr}^{-1}$ (Figure 7 A-H). In total the glacier has advanced slightly (0.07 km) since 1951.

Discussion

Mount Meager glaciers

We have provided a first-order description of the activity of Mount Meager glaciers over the past 69 years (1947-2006 documented by aerial photographs; 2006-2016 documented by Lidar). Job, Affliction, and Plinth glaciers experienced minor advances in the late 1960s and 1970s, as did most glaciers in nearby Garibaldi Provincial Park, arguably in response of negative Pacific Decadal Oscillation (PDO) (Koch et al. 2009). Devastation and Mosaic glaciers, however, retreated throughout the photo period (Figure 8).

Devastation Glacier

Our data set has allowed us to track the evolution of two large rock avalanches from the time they emplaced debris on the glacier ablation zone surface until the time the debris was deposited at the glacier front. Glacier flow progressively deformed the upstream landslide limit into a supraglacial, arched debris ridge similar in shape to a frontal-moraine. The 1947 and 1975 landslide debris moved down the glacier at a decreasing velocity over time. Between 1981 and 1990 reduction in the rate of down-wasting of the terminus is evident and possibly due to the debris input provided by the 1975 landslide or by climate forcing. The 1947 and 1975 landslide ridges were progressively dispersed by glacier flow, and as the ice stagnated at the terminus of the glacier, it generated hummocky debris. This debris is gradually being reworked and incised by Devastation Creek.

Devastation Glacier ablation zone was also debris-covered prior to the 1947 landslide, probably due to a large landslide onto the glacier in 1931 (Carter 1932) and perhaps as a result of other landslides (e.g. Bovis and Evans 1996; number 4 in Figure 1). InSAR data indicate that the steep slopes bordering Devastation Glacier ablation zone continue to deform (with up to -36 ± 10 mm over a 24-day period, measured in July-August 2016), and more large landslides are expected in this basin (Roberti et al. 2018a; Hetherington 2014), further affecting glacier activity.

The debris cover on Devastation Glacier appears to be mainly a product of large landslides directly onto the ablation zone, in contrast to the common model (Anderson and Anderson 2016) and as observed at Job, Affliction, and Plinth glaciers, where the debris is deposited in the accumulation zone, then covered by snow, and transported as englacial debris to the ablation zone where it gets eventually exposed, and slows surface melting.

Mosaic Glacier

Rapid retreat of Mosaic Glacier between 1962 and 1964 may have caused the Little Ice Age lateral moraine to collapse onto the glacier, in a manner similar to that documented by Blair (1994) at Tasman Glacier in the Southern Alps of New Zealand. The Mosaic landslide probably did not affect the glacier's mass balance because it was limited to the glacier front. The debris did not form a moraine in the glacier foreland. The lack of significant debris cover on Mosaic Glacier may explain why it retreated over the photo period in contrasts with nearby Job and Affliction glaciers, which are partially debris covered and experienced short lived advances. West and east flanks of Mosaic Creek have tension cracks and are actively deforming and Roberti et al. (2018a) undertook SqueeSAR analysis of the 1992-2000 ERS data which shows up to -7 mm yr^{-1} line of sight (LOS) displacement and DInSAR results suggest higher activity during early Summer, arguably in response of spring snowmelt.

373 *Job Glacier*

374 Like Mosaic and Affliction glaciers, Job Glacier experienced accelerated retreat between
375 1962 and 1964. The glacier advanced in the late 1960s and 1970s and has retreated since.
376 Diffuse volcanic gas emissions were observed in the Job catchment the 1970s (Peter Read,
377 personal communication, 2018) and were studied during geothermal exploration in the area
378 (NSBG 1980, 1981). The presence of fumaroles near the center of a landslide collapse scar
379 may indicate a relation between hydrothermal activity and large Holocene landslides in the
380 basin (Figure 1; Jordan 1994; Friele et al., 2008). The relation between past and ongoing
381 deformation and hydrothermal activity needs to be addressed in more detail. InSAR data
382 show that other slopes in the catchment are unstable and slowly moving, and of particular
383 concern in West flank of Plinth Peak, which had up to 34 ± 10 mm over a 24-day period in
384 July-August 2016 (Roberti et al. 2018a). This slope was partially covered by glacier ice
385 during the Little Ice Age (Holm et al. 2004) as the slope that failed in 2010 near Capricorn
386 Glacier. Job Glacier has been eroding, loading and unloading the base of the Plinth's slope,
387 and the slope shows smaller collapses and displacement along a major failure plane (see
388 Figure 6.2 in Roberti 2018a). The same conditions have been observed in Capricorn Valley,
389 at the location of the pre-2010 failure slope (Roberti et al. 2018b). Catastrophic failure of the
390 west flank of Plinth may generate a long-runout landslide, possibly one order of magnitude
391 larger than the 2010 Mount Meager landslide.

392 *Affliction Glacier*

393 Affliction Glacier, like Job Glacier, retreated at an accelerated rate between 1962 and 1964,
394 and advanced in the late 1960s and 1970s. The debris-covered streak on the west side of
395 the glacier, which is visible in each data set, is a product of frequent rockfalls from the cliff
396 above. Bovis (1990) documented slope deformation on the valley flank (up to 285 mm
397 horizontal displacement over a period of 7 years), and Roberti et al. (2018a) measured
398 current rates of this deformation using InSAR methods (up to 10 mm yr^{-1} along line of sight

399 displacement) and DInSAR results suggest higher activity during early Summer, arguably in
400 response of spring snowmelt.

401 *Plinth Glacier*

402 Plinth Glacier is the only glacier on the Mount Meager volcanic complex that was larger at
403 the end of the photo period than at the beginning. It also is the smallest and lowest of the
404 glaciers that we studied (Table 3) and formed in the ca. 2400 yr BP eruption crater. The high
405 headwalls that surround the glacier reduce incident short wave radiation and are likely the
406 reason the glacier has advanced (i.e., it has a lower equilibrium line elevation compared to
407 those of the other glaciers), albeit by only 0.07 km since 1951. In addition, the head walls
408 funnel snow avalanches onto the glacier, supplementing mass added by direct winter
409 snowfall. The headwalls consist of highly fractured and altered volcanic rocks, and generate
410 numerous rockfall and small rock avalanches that introduce debris onto the glacier.

411 Where debris on a glacier is thick, especially in the accumulation zone, it may completely
412 suppress surface melting, causing the glacier to slowly advance downvalley, in a manner
413 similar to a rock glacier (Menounos et al. 2013, Anderson and Anderson 2016, Anderson et
414 al. 2018). Plinth Glacier may provide an example of this behavior, but in situ measurements
415 and observations are needed to test this hypothesis. In a warming climate, thawing of
416 formerly frozen rock walls above glacier surfaces may increase the incidence of rockfalls
417 (Gruber and Haeberli 2007, Pogliotti et al. 2008), leading to a thickening of debris on
418 glaciers, especially if the rock walls comprise highly fractured and altered volcanic material,
419 such is the case at Plinth Glacier. Terrestrial laser scanner and photogrammetry surveys
420 could determine rockfall magnitude and frequency from the headwalls of Plinth Glacier, as
421 has been done locally in the European Alps (Fischer et al., 2006; Bertotto et al., 2015).

422 **The value of SfM and historic photographs**

423 We documented nearly 60 years of glacier activity and landslides at Mount Meager by
424 processing historic aerial photographs using SfM photogrammetric methods. This approach

offers numerous opportunities to exploit an under-utilized resource to quantify landscape change over the past ~100 years. The method has not yet achieved its full potential because of the difficulty of assessing the quality of the SfM-derived products resulting from aerial photographs that are in poor condition or that lack adequate ground control. Here we apply a method that does not require high-quality ground control and where measurements can be made in relative coordinate systems.

The advantages of processing historic aerial photographs with SfM include a fast, user-friendly workflow, retrieval of information from photos that cannot otherwise be processed due to lost metadata or poor photo condition, visualization of large areas at high resolution in 3D, and multiple years of coverage. This approach is also faster and less expensive than traditional digital photo interpretation. In the case of this study, the current cost of original aerial photographs in digital version, when available through the British Columbia digital airphoto library, is CDN \$ 18.50 per image (BC Government 2020). The theoretical cost (theoretical because not all the images are available in digital format) would have been CDN \$10,508. Such costs would have been prohibitive for this study. As these photos were in an archive, the main cost was time to retrieve and scan the photos.

In contrast with classic stereo-photo interpretation, SfM reduces the time to analyze the photos, notably, in this study we processed more than 568 photos with up to 116 photos in a single project (Supplementary material B). Moreover, by having the 3D model built by the computer, rather than by the brain of the human operator, the 3D model exist by itself and can be shared and analyzed by others. This allows other people to quickly access the same topographic information and can also be used to inform non-specialist. For example anyone can now visualize Mosaic glacier from 1951 to 2016 here: https://youtu.be/DL_SIEAvYn0) and the south flank of Mount Meager from 1948 to 2010 here (<https://www.youtube.com/watch?v=Pe-5uZEHxAl>) without the need of a stereo-viewer, tens of stereo-photos, and the training to use a stereo-viewer and the time to flicker through the pictures.

In summary, we have been able to document geomorphic changes in a hazardous area that we could not otherwise have done and have improved geohazard assessments at Mount Meager (e.g. Haley and Friele, 2018; Roberti et al., 2018a; Warwick et al., 2019). The main disadvantage of this method is the poor precision in term of coordinates that affects position and volume comparison. But there is no practical alternative to manage this amount of data with good precision. Hence, this approach could be more broadly applied, for example in studies of landslides, debris flows, flooding, and land use, both for scientific research and in private sector hazard assessments (e.g. <https://www.youtube.com/watch?v=P2pBBaxtYqk>, Cordilleran Geoscience, 2018, the Village of Lions Bay, from 1939 to 2004).

New 3D datasets generated using this approach may also elucidate the effects of recent climate change and human impacts on landscapes. The datasets have potential commercial and educational applications. Mount Meager is a protected area, and this information on historical changes can also be used for outreach, for increasing awareness of the dynamic nature of the landscape, for example how glaciers change and landslides develop, and the use of geoheritage in preserving such landscapes and managing territorial sustainable development can greatly benefit from records of dynamic change (e.g. Vereb et al. submitted). Three-dimensional topographic models can now be easily visualized and analyzed in virtual and augmented reality environments (e.g. Onsel et al., 2018, Tibaldi et al., 2020) and can be used to generate 3D time-lapse videos of surface changes (for example, see changes of Mosaic Glacier from 1951 to 2016 which can be accessed here: https://youtu.be/DL_SIEAvYn0).

Summary and conclusions

We have applied Structure from Motion (SfM) to historic vertical aerial photographs to document nearly 60 years of glacier and landslide activity at Mount Meager, focusing on Devastation, Mosaic, Job, Affliction, and Plinth glaciers. Of the five glaciers studied, debris-free Mosaic Glacier retreated the most over the photo study period (1.9 km). Devastation

Glacier retreated 1.7 km, but its retreat was perturbed by large landslides in 1947 and 1975. The 1947 and 1975 landslides temporarily increased ice velocity on Devastation Glacier and led to the stagnation of the glacier front. Job and Affliction glaciers advanced in the late 1960s and 1970s, but only 0.7 and 0.3 km, respectively. Job Glacier is located in a large landslide-generated amphitheatre in which there has been fumarolic activity since at least 1947. Plinth Glacier is located in the crater of the 2400-year-old Mount Meager eruption and is the only glacier that advanced over the entire study period.

SfM allows for reconstruction of geomorphic changes from historical aerial photographs over large areas, when ground control, image and flight metadata are unavailable. We present a workflow that does not require high-precision ground control by making measurements in a relative coordinate system. 3D historic photographic reconstruction has many underappreciated applications. It provides value to otherwise unused archival photographic datasets and facilitates documentation of recent geomorphic changes. Visualization of 3D models derived from these datasets also helps non-scientific users understand the dynamism of natural processes and the effects of modern climate change on the landscape. This information is critical for territorial planners, hazard awareness and the development of geoheritage in protected areas to increase the resilience of a territory.

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- 738

739 Table captions

- 740 Table 1 Aerial photograph and PhotoScan model characteristics.
- 741 Table 2 RMSE_x, RMSE_y, RMSE_z, RMSE_r, HA 95, and VA 95 for the different photo
742 datasets.
- 743 Table 3 Glacier parameters.
- 744 Table 3 note: a = referenced to the 1947 dataset. b = referenced to the 1951 dataset.

Figure captions

- Figure 1 Overview of the Mount Meager volcanic complex showing the extent of glaciers in 2016, landslide scars and their references to studies, unstable areas (from Roberti et al 2018a), and figure locations. (Insets: A) Figure 3; B) Figure 4; C) Figure 5; D) Figure 6; E) Figure 7). Base map: Lidar 2015-2016. Map created in ArcMap.
- Figure 2 SfM workflow from photo digitization to orthophoto and DSM production, and quality control.

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Figure 3 Devastation Creek valley from 1947 to 2016, showing changes in Devastation Glacier, moraines, landslide deposits, landslide scars, and cracks. A) 1947: Glacier at its maximum extent; note the 1947 landslide deposit. B) 1962: Active ice upstream of the 1947 landslide deposit has deformed the landslide debris into a flow-transverse arched ridge. C) 1973: The front of the debris-covered glacier has receded, and the 1947 landslide debris has moved farther downvalley. D) and E) 1981 and 1990: Active ice upstream of the 1975 landslide has deformed the debris into a flow-transverse arched ridge, and the glacier front has receded farther; note the 1975 landslide scar. F) 2006: Further retreat of the glacier. G) 2016 (Lidar data): Further retreat of the glacier. H) 2016 (Lidar data) showing glacier outline. I) Summary of changes in the position of the glacier front over the study period. Note the decrease in the recession rate during the 1962-1973 and 1981-2006 periods. m = metres; yr = years.

Figure 4 Mosaic valley from 1951 to 2016, showing changes in Mosaic Glacier, landslide deposits, landslide scars, and cracks. The glacier has retreated since 1951. A) 1951. B) 1962. C) 1964: Note that part of the lateral moraine collapsed onto the glacier. D) 1973. E) 1981. F) 1990. G) 2006: Note that the landslide deposit has been removed by erosion. H) 2016 (Lidar data). I) 2016 (Lidar data) showing glacier outline. J) Summary of changes in the position of the glacier front over the study period. m = metres; yr = years.

Figure 5 Job valley from 1947 to 2016, showing changes in Job Glacier, unstable slopes, landslide scars, landslide deposits, and fumaroles. The glacier retreated between 1947 and 1964, advanced between 1964 and 1981, and retreated again between 1981 and 2016. A) 1947: Note the dark spot on the glacier marking the location of a fumarole. B) 1951. C) 1962. D) 1964. E) 1973. F) 1981. G) 1990: Note debris on the glacier. H) 2006. I) 2016 (Lidar data). J) 2016 (Lidar data), showing glacier outlines. K) Summary of changes in the position of the glacier front over the study period. m = metres; yr = years.

783 Figure 6 Affliction valley from 1947 to 2016, showing changes in Affliction Glacier and
784 unstable slopes. Note persistent debris cover on the west side of the glacier.
785 The glacier retreated between 1947 and 1964, advanced between 1964 and
786 1981, and retreated again between 1981 and 2016. A) 1947. B) 1951. C)
787 1962. D) 1964. E) 1973. F) 1981. G) 1990. H) 2006. I) 2016 (Lidar data). J)
788 2016 (Lidar data), showing glacier outlines. K) Summary of changes in glacier
789 front position during the study period. m = metres; yr =years.

790 Figure 7 Plinth Glacier between 1951 and 2016, showing glacier outlines and ca.
791 2400-yr eruption crater/landslide scar. The glacier advanced between 1951
792 and 1990, retreated between 1990 and 2006, and advanced again between
793 2006 and 2016. A) 1951. B) 1962. C) 1964. D) 1973. E) 1981. F) 1990. G)
794 2006. H) 2016 (Lidar data). I) 2016 (Lidar data) showing glacier outlines. J)
795 Summary of changes in the glacier front position during the study period. m =
796 metres; yr =years.

797 Figure 8 Comparison of average rates of glacier retreat/advance on Mount Meager
798 between 1947 and 2016. '0' corresponds to the glacier front position in 2016.

Table 1 Aerial photographs and PhotoScan model characteristics

Year	Number of pictures	Approximate photo scale	Pixel size (m/pixel)	3D error (pixel)	3D model precision (m)	DEM pixel size (m/pixel)
2006	114	1:13000	0.5	1.2	0.6	2
1990	89	1:13000	0.5	3.0	1.5	2.2
1981	51	1:20000	0.7	1.1	0.8	2.7
1973	116	1:13000	0.5	1.1	0.6	1.9
1964	29	1:25000	1.3	1.4	1.8	5
1962	108	1:15000	0.5	1.4	0.7	1.8
1951	11	1:60000	2.2	1	2.2	4.3
1947	50	1:20000	1.1	1.4	1.5	4.3

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Table 2 RMSE_x, RMSE_y, RMSE_z, RMSE_r, HA 95, and VA 95 for the different photo datasets

Year	RMSE _x	RMSE _y	RMSE _r	RMSE _z	HA 95 (m)	VA 95 (m)
2006	10	9	13	25	23	49
1990	6	9	11	8	19	15
1981	11	12	16	40	28	78
1973	29	41	50	25	86	49
1964	23	28	36	30	62	59
1962	15	8	17	90	30	176
1951	13	22	25	14	25	28
1947	20	28	35	17	61	34

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Table 3 Glacier parameters.

Glacier	Accumulation zone elevation (m. asl)	Glacier front elevation in 2016 (m. asl)	Glacier front elevation in 1947/51 (m. asl)	Headwall height (km)	Watershed (km ²)	Relative front position in 2016 (km)
Devastation	2200	1400	1150 ^a	0.7	3	-1.7
Mosaic	2200	1600	1500 ^b	0	2.5	-1.9
Job	2000	1200	1100 ^a	0.5	4	-0.7
Affliction	2200	1500	1350 ^a	0.3	3.6	-0.3
Plinth	1700	1200	1250 ^b	1	1.5	+0.07

Table 3 note: a = referenced to the 1947 dataset. b = referenced to the 1951 dataset.

No.	Age	Reference
1	1986 AD	Evans 1987
2	2010 AD	Guthrie et al., 2012
3	1972 AD	Jordan 1994
4	1947 AD	Read 1978
5	1975 AD	Mokievsky-Zubok 1977
6	1931 AD	Carter 1932
7	2006-2010?AD	This study,
8	1975 AD	Mokievsky-Zubok 1977
9	7900, 4400BP	Friele & Clague 2004
10	370 BP	McNeely & McCuaig 1991
11	2350 BP	Hickson et al., 1999
12	6250 BP	Friele et al., 2005
	2600 BP	Friele et al., 2005
	2240 BP	Friele et al., 2008
	1860 BP	McNeely & McCuaig 1991
	870 BP	Jordan, 1984
	630 BP	Friele et al., 2008

B

D

C

11

Plinth Peak

12

1

Meager Peak

2

3

Lillooet River

Capricorn Creek

A

4

5

8

7

6

Devastation Peak

10

9

Devastation Creek

Meager Creek

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Fumarole

Inset

Unstable slope

Scar

Glaciers, 2016

Volcanic rocks

N

2 km

Pacific Ocean

BC

Mt Meager

Vancouver

I

0.5 km

- Glacier
- Landslide deposit
- Moraine
- Crack
- Landslide scar
- Unstable slope
- Reference line

- 1 1932 Landslide:
- 2 1947 Landslide:
- 3 1975 Landslide:
- 4 Undated Landslide:

A:1951

B:1962

C:1964

D:1973

E:1981

F:1990

G:2006

H:2016

J

0.5 km

Glacier

Landslide deposit

Landslide scar

Unstable slope

Reference line

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